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Microwave emissivity characteristics of soil at 10.45 GHz for remote sensor data

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Abstract : In the present paper, an attempt has been made to measure the complex dielectric constant of soil under laboratory condition at 10.45 GHz using the infinite sample method. Emissivity, both for vertical and horizontal polarization, have been calculated using measured dielectric data and emissivity model. It is found that dielectric constant and emissivity depend upon moisture contents. The measured values of dielectric constant and emissivity are compared with calculated values using Wang-Schmuggee empirical model and Dobson *et al* empirical model. It is found that both calculated and experimental values are in close agreement. The brightness temperature (Ta) of soils are also calculated with moisture contents using emissivity data.

Keyowrds : Microwave frequency, emissivity, dielectric constant, soil characteristics, brightness temperature.

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1. Introduction

The ground based studies of the emissivity properties of different earth constituents at microwave frequencies are important as they provide a successful interpretation of various remote sensor's data. Microwave emissivity of soil is dependent on both the water content and physical characteristics of soil. Emissivity is the very important parameter which provide information about soil. It is defined as the ratio of energy emitted by an object to that emitted by a perfect black body maintained at the same physical temperature and is also the ratio of brightness temperature to the physical temperature of object. The emissivity of soil depends upon its dielectric constant, surface roughness, chemical compositions, physical temperature, frequency, polarization and angle of observation. The emissivity of the soil also varies in different moisture contents. The knowledge of the emissivity of the soil is useful for building microwave sensors and microwave instrument for its application in agriculture. Various theoretical models have been developed to estimate microwave emissions of natural earth materials.

In the present paper, dielectric constant of soil samples are measured using X-band microwave bench with different amount of moisture contents at 10.45 GHz. The emissivity of soil are calculated (using emissivity model and dielectric constant) as a function of moisture contents and angle of observation.

2. Materials and method

2.1. Physical characteristics of soil :

The physical characteristics of soil depends upon its texture and amount of water presents in the soil. Amount of water presents in a soil plays a vital part in the hydrological cycle, in that it supplies water for growth of the plant ecosystem. Each soil has its own set of properties depending on its nature. Soil is characterized by sand , silt and clay. Depending upon the percentage of each constituents, the soil is named differently. The samples of soil were collected from four different places, Sample 1 and sample 2 from Man river of Surguja district, Sample 3 and Sample 4 from different places of Ambikapur city in the

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state of Chhattisgarh. The soil samples were passed through a sieve of mesh no. 50 and then collected in a metallic tray. The samples were analyzed for its texture structure and their constituents have been shown in Table 1.

Table 1. Constituents of soil samples.

Sample No.	Sand %	Silt %	Clay %	WP	W_t	γ	Density	Porosity
1.	67.4	27.8	4.7	0.067	0.197	0.368	1.72	0.351
2.	6.67	29.1	4.2	0.045	0.187	0.374	1.82	0.313
3.	50.3	34.7	10.1	0.083	0.205	0.364	1.79	0.325
4.	47.9	13.6	35.6	0.207	0.264	0.329	2.00	0.246

The moisture content in percentage is calculated as

Wc (%) = [{(Wt. of wet soil – Wt. of dry soil)/Wt. of dry soil}] × 100.

2.2. Measurement of dielectric constant :

The technique used in dielectric constant measurement programme was the infinite sample method described by Altschuler [1]. A X-band microwave bench with a slotted section and crystal detector were used for the measurement of VSWR and shift of minima needed in this technique. The complex dielectric constant (ε) was determined using the relation [1]

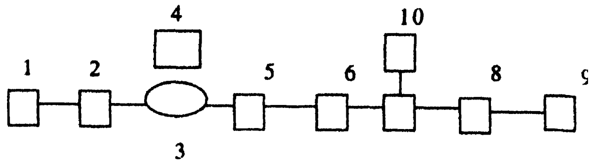
$$\varepsilon = \varepsilon' - j\varepsilon'' = [\{1/1 + (\lambda_c/\lambda_g)^2\} + \{1/1 + (\lambda_g/\lambda_c)^2\}]$$
$$\times [R-j \tan\{k(D - D_R)\}/1 - jR \tan\{k(D - D_R)\}], \quad (1)$$

where λ_c, λ_g and k are the cut-off wavelength, guide wavelength and wave vector respectively; R is the voltage standing wave ratio (VSWR) and D and D_R are the positions of first minima with and without the sample connected. The samples were filled and pressed manually in a 50 cm long wave-guide and it was terminated in a matched load. The value of D, D_R and λ_c were determined using a dial indicator on the slotted line section (least count 0.001 cm). The VSWR values were determined using double minimum power method [1,2]. The techniques of measurement are described in Figure 1.

2.3. Wang and Schmuggee empirical model :

Wang and Schmuggee [3] proposed that the complex dielectric constant of soil water mixtures can be obtained by mixing the permitivities of ice, water, rock and air are given as

$$\varepsilon = W_c\varepsilon_x + (P - W_c)\varepsilon_a + (1 - P)\varepsilon_r, \quad W_c \le W_t$$
$$\text{with} \quad \varepsilon_x = \varepsilon_i + (\varepsilon_w - \varepsilon_i)(W_c/W_t)\gamma \quad (2)$$



(1) Klystron power supply, (2) Klystron with mount, (3) Circulator, (4) Matched load, (5) Variable attenuator, (6) Frequency meter, (7) Slotted section, (8) E-H Tunner, (9) Sample holer, (10)VSWR meter.

Figure 1. Experimental set up for measurement of dielectric constant of soil at 10.45 GHz.

and

$$\varepsilon = W_t\varepsilon_x + (W_c - W_t)\varepsilon_w + (P - Wc)\varepsilon_a + (1 - P)\varepsilon_r, \; W_c > W_t \quad (3)$$

with

$$\varepsilon_x = \varepsilon_i + (\varepsilon_w - \varepsilon_i)\gamma,$$

where W_c is the fractional moisture content = (1/100) [W_c (%)], and W_t is the transition moisture which is an adjustable parameter, P is the porosity of dry soil and ε_a, ε_w, ε_r and ε_i are the dielectric constant of air, water, rock and ice, respectively; ε_x stands for the dielectric permittivity of the initially adsorbed water and γ is a parameter which can be chosen to the best fit with experimental data.

Wand and Schmuggee [3] applied the regression analysis related to the values of W_t and wilting point (WP) of the soil by the relation

$$W_t = 0.49 \text{ WP} + 0.165, \quad (4)$$

$$\gamma = -0.57 \text{ WP} + 0.481, \quad (5)$$

where W_t and γ are having the dimensions of WP which is a volume ration (cm^3/cm^3). The WP can be calculated by the texture of the soil using the following relation [3]

$$\text{WP} = 0.06774 - 0.00064 \times \text{Sand} + 0.00478 \times \text{Clay}, \quad (6)$$

where sand and clay are sand and clay contents in percent of dry weight of the soil. The values of WP, W_t, γ and porosities along with the texture information of the soil samples used in this study are shown in Table 1.

2.4. The Dobson empirical model :

In this model, the fractions of free and bound water are computed using a detailed description of the soil structure. Bound water is related to an empirical constant shape factor α another coefficients β takes the soil texture into account. This model is commonly used over the frequency range 4–18 GHz. The complex soil permittivity is written as [4]

$$\varepsilon = \{1 + \rho_b/\rho_s(\varepsilon_r^{\alpha} - 1) + W^{\beta}\varepsilon_{fw}^{\alpha} - 1) - W\}^{1/\alpha}, \quad (7)$$

where ρ_s, ρ_r, ε_r, ε_{fw} are respectively, the soil volumetric moisture, the dry soil and solid rock densities and the solid rock and free water dielectric constants. The dielectric constant of free water is the frequency and temperature dependent. It is given by a Debye-type equation

$$\varepsilon_{fw} = [\varepsilon_{w\infty} + \{(\varepsilon_{w0} - \varepsilon_{w\infty})/(1 + 2\pi f \tau_w j)\} - \{j(\sigma_i(\rho_r - \rho_s)/2\pi f \varepsilon_0 \rho_r W)\}],$$

where f, σ_i, τ_w, $\varepsilon_{w\infty}$, ε_{w0}, ε_0 are respectively, frequency (in hertz), effective ionic conductivity, relaxation time of saline water, optical limit of ε_{fw}, static dielectric constant of saline water and permittivity of free space. For silt loam, optical values of ρ_r and salinity are 2.66 and 0.738 × 10^{-3} respectively, α takes constant value of 0.65 β and σ are empirically related to sand and clay fraction from laboratory measurement.

The real par of β is

$$\beta'_\varepsilon = 1.275 - 0.519S - 0.152C \tag{8}$$

and imaginary part of β is

$$\beta''_\varepsilon = 1.275 - 0.519S - 0.152C. \tag{9}$$

σ_i, the effective conductivity is given by

$$\sigma_i = -1.645 + 1.939\rho_s - 2.2560S + 1.594C,$$

where ρ_s is the bulk density in grams per cubic centimeter (ρ_s) = 1.52 mg/cm^3, S and C represents the mass fractions of sand and clay respectively.

2.5. *Microwave emission model :*

Different theoretical models have been developed by Schmuggee [5] and Burke *et al* [6]; Coherent model by Stogryn *et al* [7] and emissivity model by Peak and Chowdhury [8] for estimation of microwave emissivity from soil surface. In this paper, we used simple emissivity model based on Fresenel coefficient derived from surface reflectivity. In this system, microwave emission from a soil surface at polarization $p = \{v,h\}$ can be measured in terms of brightness temperature T_B. For polarization p (*i.e.* vertical v) or horizontal (h)), the brightness temperature can be written as [8]

$$T_B = e_p(\theta)T + r_p(\theta)T_{sky}, \tag{10}$$

where $e_p(\theta)$ is the emissivity of the surface layer, p referes to the polarization either vertical or horizontal, $r_p(\theta)$ the reflectivity at air soil interface, T is the surface temperature and T_{sky} is the brightness temperature equivalent to the sky and atmospheric radiation incident on the soil

The emissivity $e_p(\theta)$ can be written as

$$e_p(\theta) = (1 - r_p(\theta)). \tag{11}$$

In case of smooth surface, over a homogenous medium, $r_p(\theta)$ can be obtained from Fresnel reflection coefficient $R_p(\theta)$ as

$$R_p(\theta) = |R_p(\theta)|^2.$$

Fro horizontal polarization, $R_p(\theta)$ is calculated as

$$R_p(\theta) = \{\cos\theta - (\varepsilon - \sin\theta)^{1/2}\} / \{\cos\theta + (\varepsilon - \sin\theta)^{1/2}\} \tag{12}$$

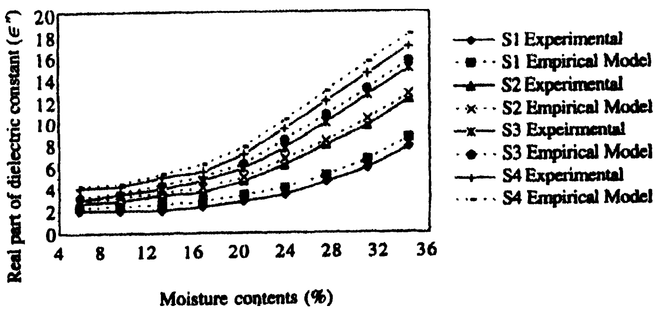
and for vertical polarization, $R_p(\theta)$ is calculated as

$$R_p(\theta) = \{\varepsilon\cos\theta - (\varepsilon - \sin\theta)^{1/2}\} / \{\varepsilon\cos\theta + (\varepsilon - \sin\theta)^{1/2}\}, \tag{13}$$

where θ is the angle of observation from nadir and ε is dielectric constant of the soil. Equations (10)–(13) can be used for the calculation of emissivity, provided that the dielectric constant of the soil with moisture content is known, The brightness temperature T_B can be computed using eq. (10) after knowing the values of T, $r_p(\theta)$, T_{sky}.

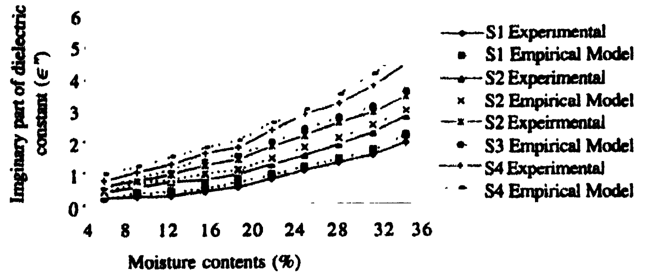
3. Results and discussion

The values of dielectric constant both ε' and ε'' with moisture contents for four soil samples used in this study are shown in Figures (2) and (3). It shows that the dielectric constants of the soil samples increase with the increase in moisture contents. The increase in ε' is rapid compared to that in ε'' with moisture contents. The dielectric constant ε' increases slowly upto 12% moisture contents and thereafter it increases rapidly. The initial slow increase in the dielectric constant upto 12% moisture contents may be due to less number of free water molecules. At higher moisture contents, the number of free water molecules in the soil water mixture increase. The free water molecules



S1-Sample 1 : S2-Sample 2 : S3-Sample 3 : S4 Sample 4

Figure 2. Variation of real part of dielectric constant of different soil samples with moisture contents (%). Solid line for exerimental value and dotted line for empirical value.



S1-Sample 1 : S2-Sample 2 : S3-Sample 3 : S4 Sample 4 :

Figure 3. Variation of imaginary part of dielectric constant of different soil samples with moisture contents (%). Solid line for experimental value and dotted line for empirical value.

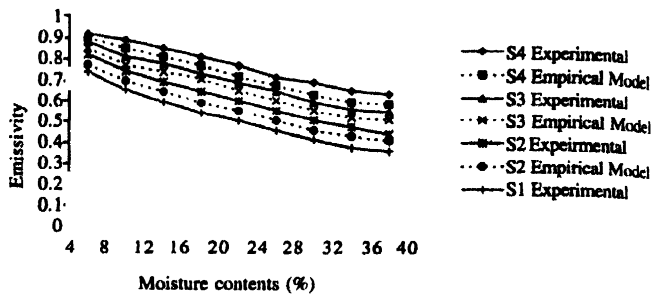
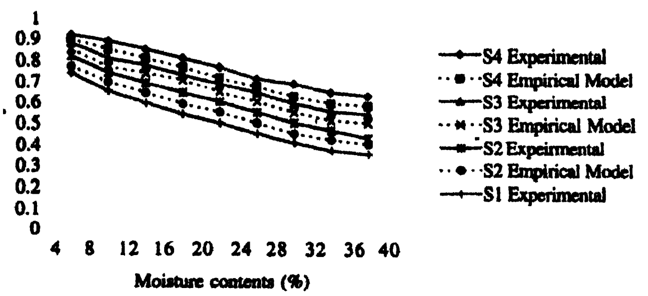


Figure 5. Variation of emissivity of different soil samples with moisture contents for vertical polarization at $\theta = 30$. Solid line for experimental value and dotted line for empirical value.

have higher dielectric constant compared to bound water molecules. Hence, it is a capillary system with less volume of capillary pores and with a large volume of non-capillary pores space which ensures good drainage and aeration and has low water holding capacity.

The measured values of dielectric constant are compared with the values obtained by the two empirical models based on soil texture [3,4]. The graph shows that the real part of the dielectric constant ε' is in good agreement with the values calculated by empirical models [3,4]. The measured values are slightly lower than calculated values. This discrepancy may be due to several reasons *i.e.*, chemical composition of soil, temperature of soil, and experimental method used for measurement of complex dielectric constant of soil.

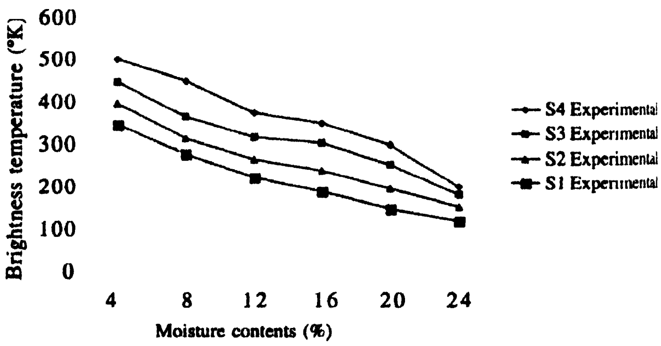
The emissivity of soil samples are calculated using emissivity model with measured and calculated values of dielectric constant for both vertical and horizontal polarization. The results obtained are shown in Figures 4 and 5. It shows that the emissivity decreases with the increasing moisture contents. It lies between 0.35 to 0.97 and never equals to unity. This happens as the moisture content increases, the number of free water molecules,



S1-Sample 1 : S2-Sample 2 : S3-Sample 3 : S4 Sample 4

Figure 4. Variation of emissivity of different soil samples with moisture contents for horizontal polarization at $\theta = 30$. Solid line for experimental value and dotted line for empirical value.

available in the soil water mixture increases. Due to increases in dielectric constant, reflectivity increases and emissivity decreases with moisture contents. Both experimental and empirical values of emissivity are in close agreements. The emissivity values lie is between 0.35 to 0.97 and never equal to unity. The emissivity values for horizontal polarization are found to be close to vertical polarization. The brightness temperature are also calculated with the help of the emissivity data. It is found that the brightness temperature decreases with the increase in moisture contents, Results obtained are shown in Figure 6.



S1-Sample 1 : S2-Sample 2 : S3-Sample 3 : S4 Sample 4

Figure 6. Variation of brightness temperature (°K) of different soil samples with moisture contents (experimental value).

4. Conclusion

Conclusions from this study are as follows :

(i) The dielectric constant of soils is strongly dependent on soil moisture and soil texture.

(ii) The laboratory studies of dielectric and emissivity properties of soils with various moisture contents, texture, temperature density, as well as other chemical and physical properties of soils are very important in correlating the remotely sensed data with actual field condition and in distinguishing targets having identical dielectric constant and emissivity properties.

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